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Pro-poor sewerage: solids modelling for design optimisation

1 **Michael Gormley** MSc, PhD, CEng, MCIBSE, MIET
Lecturer, Drainage Research Group, Heriot-Watt University, Edinburgh, UK

2 **Duncan D. Mara** PhD, DSc(Eng), CEng, CBiol, FICE, FIBiol, FCIWEM, FRIPH
Professor, University of Leeds, Leeds, UK

3 **Nicole Jean** BEng
Research Student, Drainage Research Group, Heriot-Watt University, Edinburgh, UK

4 **Ian McDougall** PhD
Computing Officer, Drainage Research Group, Heriot-Watt University, Edinburgh, UK


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More than 2·8 billion people still live without adequate sanitation. 'Simplified sewerage' is one possible solution, offering the possibility of an appropriate scale for urban sanitation. Adoption of such systems requires the range of engineering and advocacy tools erstwhile only available in developed countries. The application of small-bore solid transport system models is wholly appropriate for simplified sewerage, but modifications are required to account for the shallow gradients and the likely accumulation of solids due to low water usage. The importance of local water flow depth on drain self-cleansing where large accumulated solids are present has been identified, and the solid movement threshold has been quantified for a range of expected gross accumulated solids. These modifications, together with improved solid deposition predictions, have contributed to the development of a robust model suitable for application to simplified sewerage systems in order to improve efficiency and optimise design.

Notation

A	flow cross-sectional area (m)
B	blockage factor
C^+, C^-	characteristic slopes in an x–t plane
c	wave speed (m/s)
c_{ds}	downstream wave speed (m/s)
c_n	normal depth wave speed (m/s)
c_{us}	upstream wave speed (m/s)
D	pipe diameter (m)
dH_s	depth difference across solid (m)
g	acceleration due to gravity (m/s)
h_i	flow depth at node i
h_n	normal depth (m)
N	node number in method of characteristics
P	flow perimeter (m)
Q_w	water flow rate (l/s)
S	friction gradient (slope)
S_g	specific gravity of a solid
S_o	pipe gradient (slope)
T	water surface width (m)
V_f	flow velocity (m/s)
V_s	solid velocity (m/s)
Δx	distance increment (m)
Δt	time increment (s)

1. Introduction

1.1 Background: International development context

The basic purpose of a sanitation system is to isolate people from potentially harmful waste material. Transporting waste material in a contained drainage/sewerage system offers users the highest possible protection against disease. The most recent World Health Organization (WHO) annual assessment of sanitation and drinking water (WHO, 2010) estimates that there are some 2·6 billion people without access to adequate sanitation globally. The situation has been exacerbated by the rapid urbanisation of the late twentieth century – for the first time in recorded history there are now more urban than rural dwellers (Worldwatch Institute, 2009) Of the three billion urban dwellers, as many as one billion live in unplanned peri-urban shanty towns, 'favelas' or slums. Living on the margins of cities, most of these people do not have access to adequate sanitation provision, leading to inevitable health and quality of life issues.

The challenges set by the Millennium Development Goals (MDGs) are therefore immense. The task of halving the number of people without access to improved sanitation by 2015 is a monumental one and one that cannot ignore the urban aspect of the problem. Despite best efforts, the goal seems more elusive than ever. There is hope that the recently announced 'boost' to the impetus for attaining the MDGs for sanitation with a 'five year drive to 2015' (UNSGAB, 2011) will help, but clearly the issue is a real problem. The close correlation between access to adequate sanitation and poverty predetermines that any credible solution must be both 'low cost' and 'cost effective'. Solutions must also be capable of dealing with the growing numbers of people needing provision.

There are many potential technological solutions to the problem of providing improved sanitation. Ventilated improved pit (VIP) latrines and on-site sanitation in general are important elements of the strategy and provide on-site solutions appropriate to many rural areas with favourable groundwater conditions; however, space is at a premium in the peri-urban setting and therefore these options are not always possible or appropriate. Conventional sewerage systems are obviously desirable, but cost and access for deep excavations preclude their use in both low-income and unplanned high-density settlements.

Simplified sewerage systems, with their characteristic shallow gradients and therefore shallow excavation requirements, provide a real alternative for the many peri-urban dwellers on the fringes of large cities. The cost savings relative to conventional sewerage systems are considerable: recent analyses in India, for example, show the cost of simplified sewerage to be approximately one third of that of conventional sewerage systems (Mara, 2005; Mara and Broome, 2008; Nema, 2009). Reduced cost and ease of construction are appropriate to the socio-economic background of peri-urban communities that, in many cases, self-manage both the installation and the ongoing operation and maintenance of the system.

The design methodology for simplified sewerage is based on steady-state hydraulics, and the favoured method is to specify the pipe diameter and gradient to achieve a minimum tractive tension in the system (Mara, 1996a, 1996b). The design is based on rational changes in the design standards defining conventional sewerage that makes simplified sewerage cost-effective without sacrificing quality (Mara, 1996a, 1996b). The changes from conventional sewerage design result in small-bore pipe configurations and systems that are more similar in their characteristics to building drainage systems (BDSs) than conventional sewerage systems. Many of the time-dependent numerical predictive techniques used to model and improve BDSs are therefore applicable to simplified sewerage designs and offer real advantages in the simulation of waste solids transport.

This research seeks to extend an existing solid transport/building drainage predictive model and apply it to the shallow gradients and large 'accumulated' solids characteristic of simplified sewerage systems. The benefits of predictive modelling have been enjoyed by engineers, designers and stakeholders in the developed world for many years. For community-managed simplified sewerage systems the stakes are high. However, predictive models can increase confidence that the limited resources available are contributing to the construction of an efficient, optimised system, suitable for purpose and with a low risk of failure.

There is no doubt that achieving scale of installation is one of the biggest issues facing planners, designers and implementers of sanitation provision globally today. This scale could be achieved through the implementation of conventional sewerage systems but, as noted earlier, this is an expensive and, in many cases, an inappropriate response. A recent meeting of the UK sanitation community of practice (SanCoP) highlighted a few successful examples of implementing simplified sewerage to 'scale'. In Indonesia (Ismawati, 2011) and Tanzania (Beale, 2011), however, these are still in the minority. This paper provides the basis for a robust numerical model with the aim of creating a focus on the engineering aspects of a possible solution to the scale issue. This focus could enhance the take-up of small-bore simplified sewerage systems and lead to further advances in technology, thus creating a 'virtuous cycle' of research, innovation and implementation in order to achieve scale and meet the goal of sanitation for all in the future.

1.2 Solid transport modelling

Two conceptual models currently exist for the transportation of discrete solids in near-horizontal pipes – the velocity decrement model and the Mach number model. These conceptual models focus on the distance to deposition for solids since this is a useful measure of system performance.

The main difference between the two models is that the velocity decrement model contains boundary condition equations that operate alongside the water flow calculations; solid transport is therefore calculated in a virtual sense. The models of Swaffield and Galowin (1992), Swaffield *et al.* (1999) and Butler *et al.* (2005) fall into this category.

The second category of transportation model, due to Gormley and Campbell (2006a, 2006b), differs from the virtual model in that the presence of the solid modifies the surrounding water, which in turn modifies solid transportation – a capability that becomes essential close to deposition. This model is based on the solid Mach number in the flow and is therefore deterministic. This Mach model is particularly appropriate when solids are close to deposition, a situation characteristic of the transport of solids in pipes of shallow gradients or driven by very low intermittent flow regimes. It is considered essential to develop specific boundary equations for solids in simplified sewerage networks and to locate these boundary equations in a deterministic model where the solid itself influences the water flow and vice versa.

Another issue affecting modelling of solid transport is the impact of 'flow anomalies' on solids movement. These anomalies are usually slow-moving deeper areas of flow, such as those found behind a hydraulic jump, upstream of a junction, or the water 'pooling' behind a solid that has come to rest. For these scenarios, Gormley and Campbell proposed a 'modified Mach model' to cope with the changing nature of the transport mechanisms when a solid meets an area of non-uniform flow, again providing an advance on existing velocity decrement approaches (Gormley and Campbell, 2006a, 2006b).

While these models can accurately predict solid transport in BDSs in modern 'developed world' installations where ample piped water is generally available, it is only on long horizontal pipe runs that the accumulation of solids becomes a real issue. This phenomenon, usually associated with toilet tissue paper, occurs when the paper has been transported to a maximum distance and is then deposited; however, this process occurs along the way so solids can vary in size, shape and weight with distance. This maximum distance is due to the attenuation of the transporting surge wave, the leak flow past the solid and other contributing factors such as solid specific gravity, pipe slope and diameter and the presence or absence of joining flows from other branches.

The result of this can be a settling and partial drying out of the waste (both paper and faeces). Subsequent surge waves may carry a similar waste load that may settle on the previous, partially dried load. In this way, solid mass accumulates in the pipe and can potentially lead to pipe blockage requiring expensive remedial work. By predicting the minimum flows available at any point in the pipe under real system simulation conditions, an assessment of blockage risk can be made. By minimising the risk of blockages, the system can be optimised for minimum maintenance intervention.

2. Free surface wave modelling

2.1 Model basis

The method of characteristics is appropriate for the simulation of free surface flows in partially filled drainage pipes. Based on solution of the St Venant equations for continuity and momentum, this modelling technique represents the fundamental equations as two first-order finite-difference equations, known respectively as C^+ and C^- characteristic slopes in the method of characteristics grid, linking known conditions at time t to conditions at P at one time step in the future. With reference to Figure 1 it can be shown that

1. $$\frac{\mathrm{d}V}{\mathrm{d}t} \pm \frac{g}{c}\frac{\mathrm{d}h}{\mathrm{d}t} + g(S - S_\mathrm{o}) = 0$$

provided that the calculation time step conforms to the Courant criterion, defined as

2. $$\frac{\mathrm{d}x}{\mathrm{d}t} = V \pm c$$

where the wave propagation speed c is defined as $c = (gA/T)^{1/2}$, S and S_o are the friction and pipe slopes respectively, and A and T are the flow cross-sectional area and the surface width respectively. The form of Equation 1 requires a small base flow in the pipe in order that the calculations can begin (Lister, 1960; Swaffield and Galowin, 1992).

From Figure 1 it can also be seen that only one characteristic is available at system entry or exit. Thus, it is necessary to define boundary equations that may be solved with the appropriate C^+ and C^- characteristic at these nodes. Previous research in this area (Swaffield and Galowin, 1992) has yielded boundary equations for many conditions including

- WC discharge
- pipe junctions
- displaced upstream hydraulic jumps
- flow at the base of a vertical stack.

The grid used to represent the progress of a calculation in the method of characteristics scheme of the type most relevant to the partially filled pipe, unsteady flow regimes experienced in BDSs is also shown in Figure 1. This is a specified grid system in that the nodal distances along the x axis are pre-defined

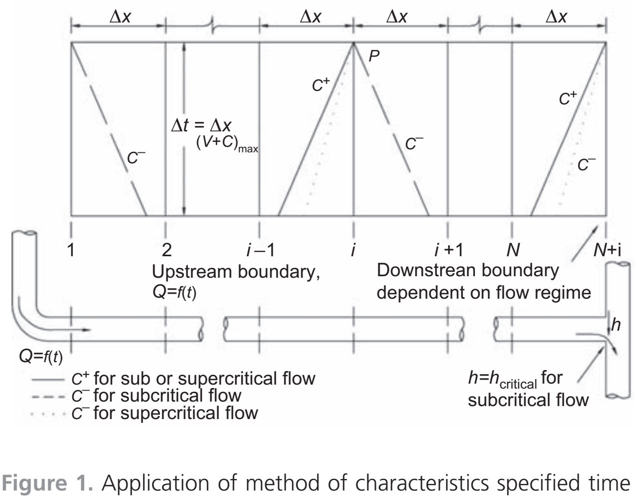

Figure 1. Application of method of characteristics specified time interval grid to partially filled pipe flow with known entry and exit boundary equations

while the time step may vary depending on the flow conditions and subject to the Courant criterion outlined earlier.

The transport of a solid in a near-horizontal drainage pipe under steady flow conditions is characterised by a number of significant changes in the flow, depth profile, as shown in Figure 2. The water height behind the solid reduces gradually to a point where the water depth is normal for the particular flow regime due to the inflow, and the water immediately in front of the solid is below normal water depth and increases downstream. This bow wave is due to the effects of water tumbling over the solid at a higher than normal velocity.

2.2 Solid boundary condition

The presence of a solid in a flow requires a simple modification to the water depth profile at the solid's location along the pipe at a given time (Figure 3). The water depth is therefore given by

3. $$h_i = h_i + \mathrm{d}H_s$$

where h_i is the water depth at node i if no solid is present and the flow can be either supercritical or subcritical; $\mathrm{d}H_s$ is the water depth difference across the solid, which is a function of the velocity of the solid V_s such that

4. $$\mathrm{d}H_s = f(V_s)$$

A gradually varied profile can then be fitted between the solid boundary and the upstream location where the flow depth returns to h_i. It should be noted that the boundary condition given by Equation 3 is valid for a solid at one location only or for the special case where a solid has deposited.

The water depth difference $\mathrm{d}H_s$ is related to V_s in that $\mathrm{d}H_s$ is at its maximum when $V_s = 0$ and $\mathrm{d}H_s$ is at its minimum when $V_s \rightarrow V_{s(max)} \rightarrow V_f$. In keeping with the general classification of water depth in terms of wave speed, then the following can also be said of the solid. When $V_s \rightarrow 0$

5a. $$\frac{c_{us}}{c_{ds}} \rightarrow \left(\frac{c_{us}}{c_{ds}}\right)_{max}$$

and when $V_s \rightarrow V_{s(max)} \rightarrow V_f$

5b. $$\frac{c_{us}}{c_{ds}} \rightarrow 1$$

where c_{us} is the wave speed at the upstream face of the solid and c_{ds} is the wave speed at the downstream face of the solid.

The 'positive' curve shown in Figure 4 shows the relationship between c_{us}/c_{ds} for a single solid of diameter 36 mm and specific gravity $S_g = 1{\cdot}05$ in a 100 mm pipe set to a slope of 1 in 100. The trend line shown represents the possible acceleration or deceleration of a solid when $c_{us}/c_{ds} \geqslant 1$, that is when there is a water depth difference across the solid and the solid is not fully buoyant. The data for this curve were obtained under normal supercritical conditions, therefore $c_{ds} \approx c_n$; in practice there is likely to be a depth depression downstream of the solid so it is usual for the following expression to be true

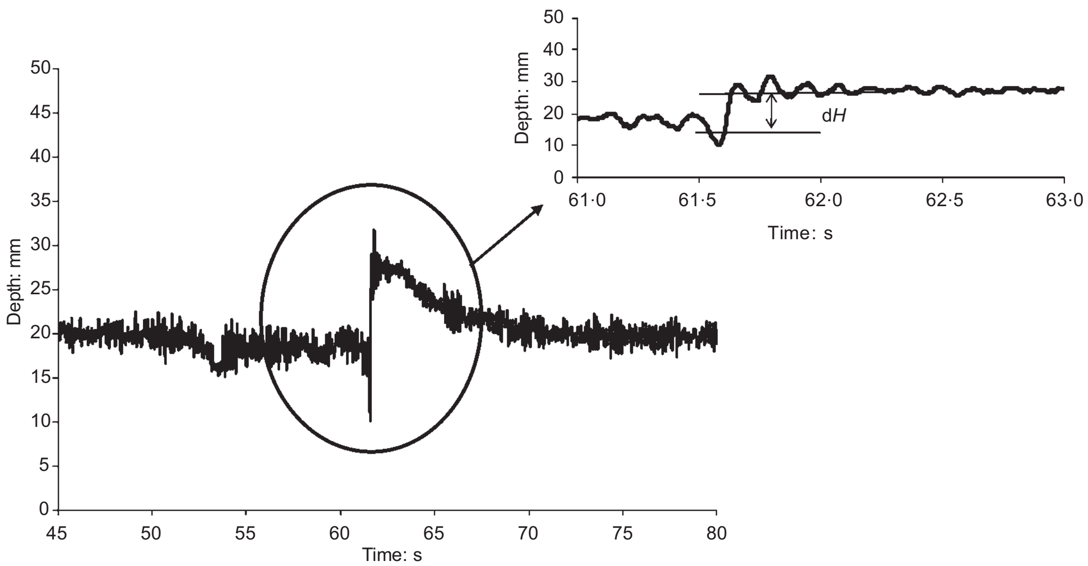

Figure 2. Water depth difference across a solid

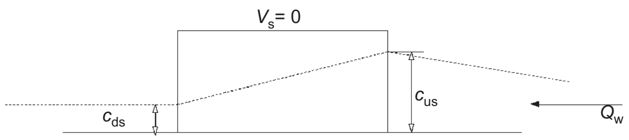

Figure 3. Characteristics of a moving solid in water

6. $c_{ds} \leq c_n$

where c_n is the wave speed of the flow at normal depth. So, the positive curve in Figure 4 is applicable when the condition in Equation 6 is met.

In the case where a solid is travelling in a flow where the flow is not supercritical then the inverse curve can be used. In this case the following condition applies

7. $c_{ds} \geq c_n$

3. Applying existing models to simplified sewerage network analysis

3.1 General

Models such as the water depth model (Butler *et al.*, 2005), flow velocity (Swaffield *et al.,* 1999) and wave speed dependent models (Gormley and Campbell, 2006a, 2006b) can all be used to simulate simplified sewerage. However, there is a requirement for an extension to the limits on the boundary conditions associated with solid transport and deposition of large solids at the shallow gradients and low-flow conditions associated with simplified sewerage networks. The preferred methodology for this research is the wave speed dependent model due to Gormley and Campbell. The advantage of this method over other 'virtual' methods such as those due to Swaffield and Galowin (1992), Swaffield *et al.* (1999) and Butler *et al.* (2005) is that it is deterministic – the presence of solids in the water modifies the surrounding water conditions, which in turn affects the transport of solids. Successful prediction of the interaction between solids and the water is essential in order to assess the performance of a simplified sewerage system where ultralow flows are expected and the accumulation of solids into larger masses is inevitable.

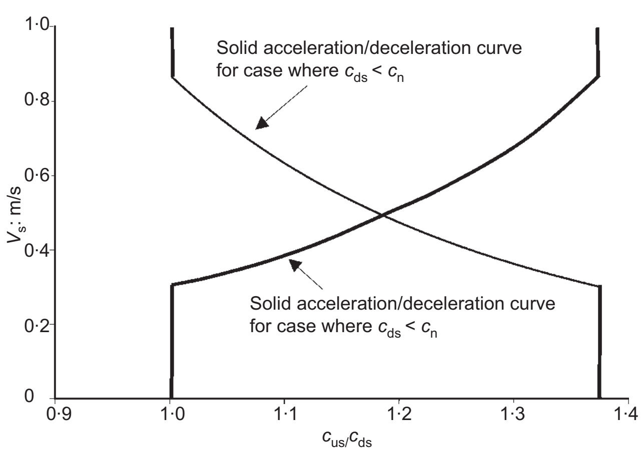

Figure 4. General form of the model

3.2 Extending the existing model for shallow slopes

The laboratory test rig used to establish these boundary conditions is shown in Figure 5 and consists of three pipes (of diameters 75, 100 and 150 mm) laid at a gradient of 1:166, a typical simplified sewerage gradient.

3.3 Choice of representative solid and methodology

Representative plastic cylindrical solids of 36 mm diameter and 75 mm length with variable specific gravity were inserted at a steady flow rate (see Figure 6 for image of this solid in a flow). These solids were first developed by the US National Bureau of Standards (NBS) in the 1980s and formed the basis for much of the work carried out to date on solid transport mechanisms in drainage systems (Gormley, 2004; McDougall, 1995; Swaffield and Galowin, 1992). As the solid travelled along the pipe the water depth behind the solid and the water depth in front of the solid were recorded. From these two variables, a graph similar to that shown in Figure 4 can be produced. This methodology was repeated for a range of solids in the three different pipe diameters.

3.4 Results and discussion

Previous research (Gormley and Campbell, 2006b) established the importance of the ratio of upstream to downstream wave speed in determining the velocity of a solid in a flow; it also predicts the deceleration and acceleration of interacting solids as they travel along a pipe. It is therefore a useful way to describe solids in a flow. Figure 7 depicts the changing nature of this relationship with changing pipe diameter for the shallow pipe gradient of 1:166 used in the experiments.

In addition to the work carried out by Gormley and Campbell, previous research on solid transport in pipes set to gradients as shallow as 1:140 was carried out by Goulding (1984). Goulding's methodology was to determine the water depth behind a solid when it was towed at different velocities, thus giving a range of water depths over a range of flow conditions. Unfortunately, Goulding's work focused exclusively on 100 mm diameter pipes and it is therefore difficult to compare across the wider range of pipe diameters investigated in this research. Data from previous investigations (Gormley and Campbell, 2006b; Goulding, 1984) together with the data from this research are presented in Figure 8. The progressive steepening of the power curve trend lines with decreasing pipe

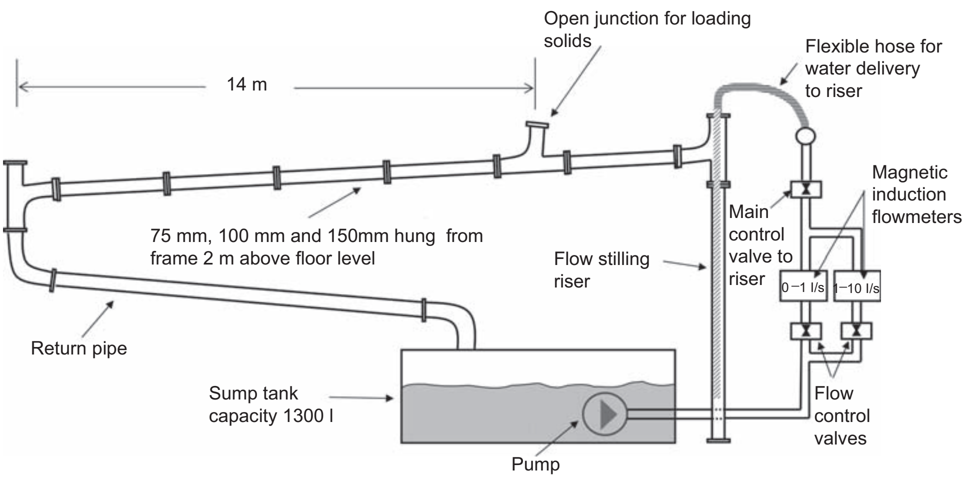

Figure 5. Laboratory test rig

gradient confirms that the results from the current work comply with the general form of the model developed by Gormley and Campbell and shown in Figure 4.

It is also of interest to note that, as the pipe gradient decreases, the maximum solid velocity decreases and the range of flow rates c_{us}/c_{ds} also decreases. This confirms that, as the gradient decreases, the effect of flow velocity diminishes and hydrostatic forces are in the main responsible for solid movement and transport. This phenomenon was observed in the laboratory as a 'stop–start' movement of the solid along the pipe. The mechanism involves the solid coming to rest, water building up behind it thus initiating movement, and then the solid being carried on by inertia until it comes to rest again where the process repeats until the hydrostatic force can no longer initiate movement. This phenomenon is of more significance in pipes set to shallow gradients as noted earlier. The stop–start process raises an additional concern in practice: that solid waste accumulates and solids become large and difficult to move. These large solids can lead to blockages and are of considerable concern in establishing limits to simplified sewerage system design.

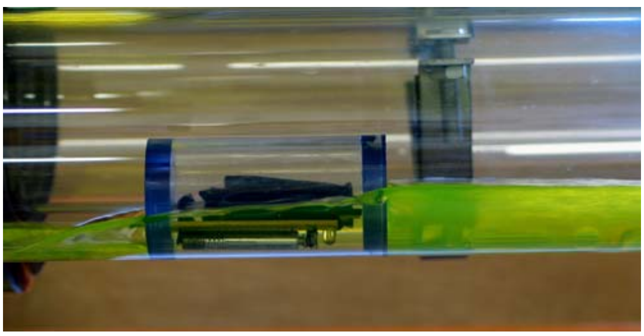

Figure 6. Cylindrical NBS solid in a flow

4. Determination of the movement threshold of large accumulated solids

4.1 General

To address the specific issue of the accumulation of large solids in simplified sewerage systems set to shallow slopes, an additional set of experiments was carried out to establish the movement thresholds for various large solids chosen to represent near blockages of the pipe. This in effect establishes the resilience of the system under ultralow water usage criteria.

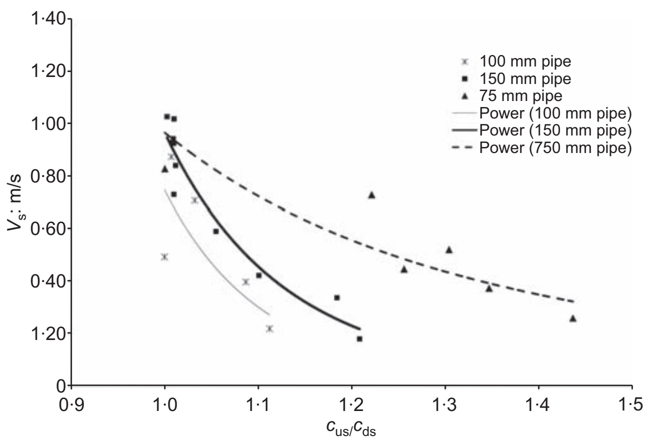

Figure 7. Ratio of upstream to downstream wave speed against solid velocity for a 36 mm diameter solid in pipes set to a gradient of 1:166

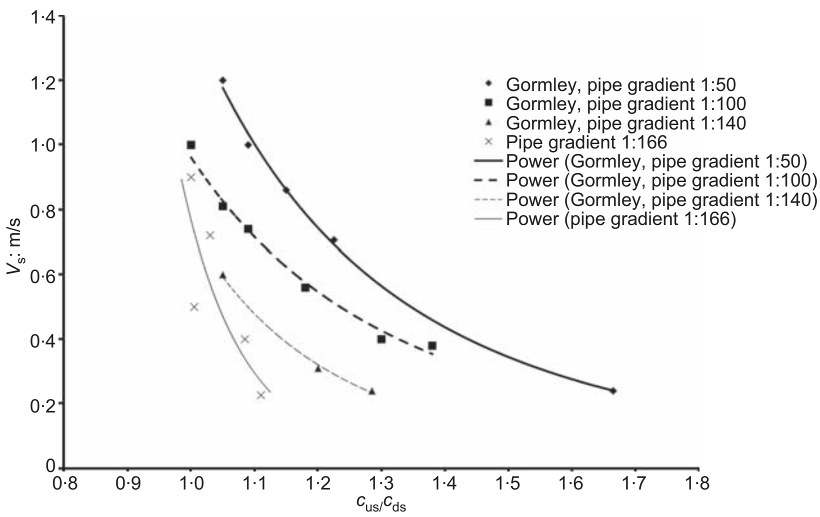

Figure 8. Data for 100 mm pipe: Gormley (Gormley and Campbell, 2006b); Goulding (Goulding, 1984)

While the movement threshold is important for solid transport, it is also a useful indicator of the risk of blockage since slow-moving solids tend to accumulate and create bigger solids that are all the more difficult to move. This issue is of significant importance to simplified sewage since the pipes are set to shallower gradients and the flows available are very low in the first instance. Any predictive model dealing with solid transport under these conditions needs to be able to cope with the movement threshold of large solids and blockages.

This part of the investigation required not only the derivation of a conceptual model to aid understanding of the mechanisms at play in moving large accumulated solids in simplified sewerage systems, but also a mathematical expression to quantify the flows required to initiate movement suitable for inclusion in a method of characteristics predictive model.

4.2 Choice of solids and methodology

The study was conducted in the Heriot-Watt University drainage laboratory test rig shown in Figure 5, using solids from composited moist hand towels bound together. In order to develop a comparative range of test results, solids representing potential pipe blockages of 20, 30 and 50% were used (Jean, 2009). The dimensions of the solids used in the test are shown in Table 1.

The methodology used was to place the mass in the pipe and subject it to a steady flow. A steady flow was used since the flows found in such systems are, in the main, quasi-steady, particularly at the point in the system where accumulation is considered a risk. Figure 9 shows an illustration of the transport mechanism near deposition where the surge wave from the appliance has abated. This phenomenon occurs at a considerable distance from the closest source and the predominant transport mechanism is hydrostatic, as water builds up behind the solids and carries them further along.

4.3 Conceptual model development

A range of solids representing various blockages were installed in the test apparatus shown in Figure 5. Figure 10 shows the simulated large solids and Figure 11 presents an image of a typical solid in the pipe. For each solid, the flow rate was increased slowly (to avoid creating a shockwave) and the solid

Blockage	75 mm ∅ pipe	100 mm ∅ pipe	150 mm ∅ pipe
20%	45 mm × 20 mm	45 mm × 30 mm	11 mm × 30 mm
30%	45 mm × 30 mm	55 mm × 60 mm	90 mm × 55 mm
50%	55 mm × 60 mm	55 mm × 70 mm	94 mm × 94 mm

Table 1. Dimensions of solids

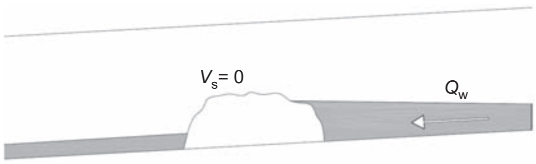

Figure 9. A large blockage in a drainage pipe at rest and the force due to wastewater applied in a horizontal direction

movement flow rate was recorded. A sample of the data collected is shown in Figure 12, clearly indicating, as expected, that, as the pipe diameter or solid specific gravity increases, the flow required to initiate movement increases.

Figure 13 illustrates the range of flow rates required to initiate movement for all the cases tested. From these data, the conceptual model of Figure 14 was developed. It can be seen that, in general again, as pipe diameter increases and the solid specific gravity increases, the flow rate needed to initiate movement also increases. It is also interesting to note that at larger pipe diameters the range of flow rates required to initiate movement is much greater for the range of solid sizes and specific gravity tested. This confirms that solid transport is generally better, and more consistent, in small-bore pipes.

4.4 Mathematical model

The data shown above were conflated in Microsoft Excel using a solver algorithm developed for the purpose. A sensitivity analysis using regressive techniques was carried out on the data and it was concluded that the best fit for the equations occurred when the normal depth of the flow rate required to initiate movement was used. It was found that the normal

Figure 10. Formation of simulated large solids

Figure 11. Typical solid in a pipe showing the build-up of water upstream

depth h_n of flow required to initiate movement of solids can be calculated from

$$h_n = [(2{\cdot}643 \times 10^{-7} B^{0{\cdot}78} - 9{\cdot}064 \times 10^{-8}) D^{3{\cdot}784} + 8{\cdot}384] S + 4{\cdot}72 \qquad (8)$$

Figure 15 shows the actual depth recorded for each blockage threshold movement and the model-predicted water depth. The R^2 value (0·9782) is considered reasonable given the variability experienced in the experimental investigation. Static friction between the solid and the pipe wall, difficulty in setting very low flow rates, and small movements in the solids as the water engulfed them were among the factors most responsible for the discrepancies observed.

4.5 Discussion

The ability of a system to self-cleanse is essential for trouble-free operation. The conceptual model developed for the threshold movement for large accumulated solids suggests that maintaining a sufficient water depth along the pipe is crucial if total blockages are to be avoided. The process is aided, however, by the creation of the partial blockage due to the accumulation of solids itself – this allows a build-up of water and this increase in hydrostatic force contributes significantly to the robust nature of simplified sewerage. This may seem counter-intuitive, but the shallow slopes facilitate a significant hydrostatic effect that is lost in systems with steeper gradients as fast-flowing water leaks past solids at a far greater rate. This phenomenon means that simplified sewerage systems make more efficient use of the water used and so contribute significantly to water conservation and water efficiency strategies.

5. Conclusions

The rapid urbanisation of the late twentieth century has provided sanitation provision challenges to policy makers,

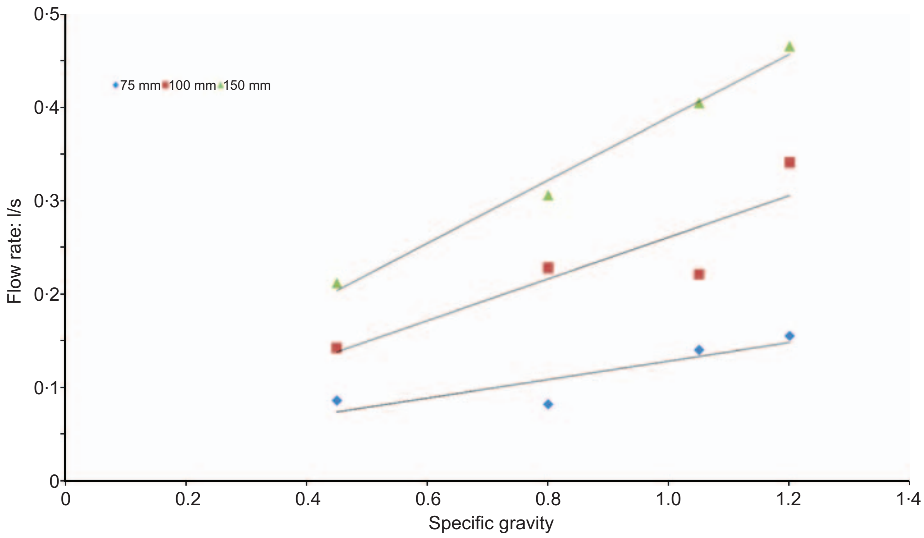

Figure 12. Flow rate against solid specific gravity S_g for a 30% blockage

planners and engineers. The scale of the problem is immense and the options of either low-cost on-site solutions or expensive conventional systems are both inappropriate in many cases. Simplified sewerage can play a significant part in addressing the problem; however, despite significant successes in Brazil and India, uptake is still slow. A paradigm shift in thinking is therefore required if real progress is to be made.

Modelling and investigating systems have led to continuous sanitation improvements in developed countries over the past two centuries and this success could be replicated in developing countries. Models act as an excellent advocate for a technology, as well as a forensic tool, building confidence in the technology through dissemination of results and initiating debate.

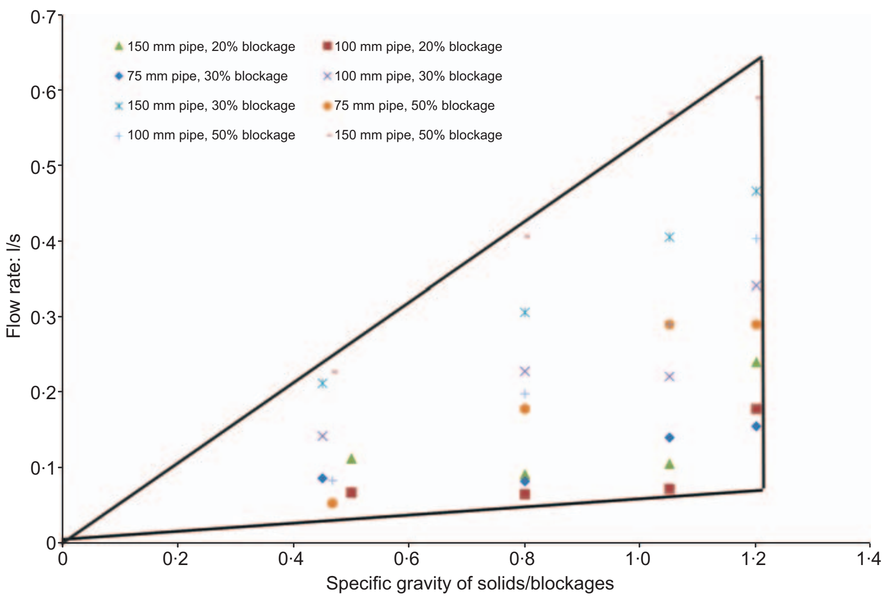

Figure 13. Range of flow rates to initiate movement for all solids/ blockages in all pipes

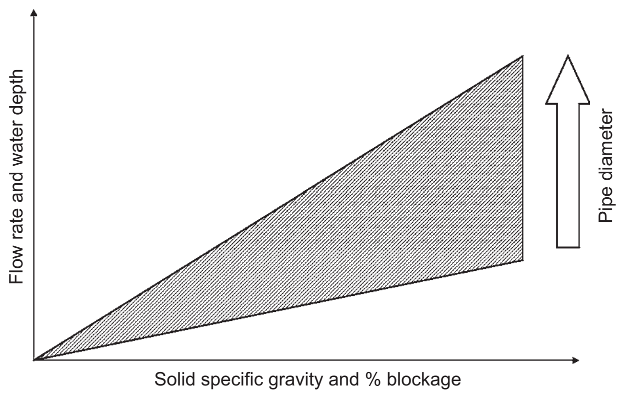

Figure 14. Conceptual model for solid movement threshold

The laboratory investigations described in this paper go a considerable way to adapting a method of characteristics based BDS numerical model for specific application to simplified sewerage systems. The investigations also define some important solid transport mechanisms relevant to such systems and confirm the following long-held beliefs among practitioners in the field.

- Smaller bore pipes are less prone to blockage.
- Local water depth and minimum tractive tension are just as important, if not more, than drain self-cleansing velocity.
- Almost counter-intuitively, under low water usage, shallow gradients promote solid transport and hence minimise blockages and help conserve water.

The results of these investigations should go some way to alleviate the fears of those policy makers and planners for whom expensive conventional systems have seemed the only option for low-income or high-density peri-urban unplanned housing. The ability to offer cost-effective sanitation provision for hundreds of households in an intervention is absolutely necessary if the noble aims set out in the MDGs are to become anything close to a reality in the near to middle future.

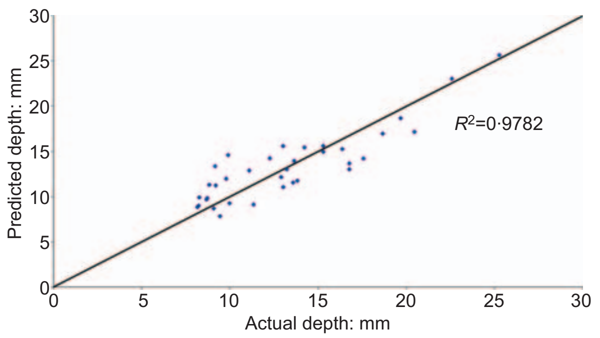

Figure 15. Predicted depth against actual depth for the model

The fundamental principles and the empirically derived equations described in this paper form the basis for an engineering-led approach to scale up potential solutions to widespread sanitation neglect of a large proportion of the world's population. To make this model more effective there is a need for further research to refine, calibrate and validate the model using real installation and usage data from the field. This will form the basis for the next phase of this work.

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